

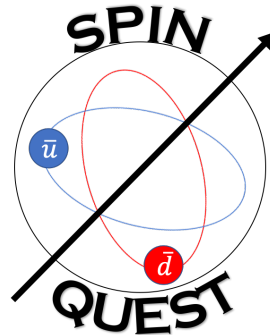
Systematic Study of Spectrometer-Induced Azimuthal Asymmetries for SpinQuest

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with

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On behalf of the SpinQuest Collaboration



FERMILAB-SLIDES-20-103-E



U.S. DEPARTMENT OF
ENERGY

Office of Science

Outline

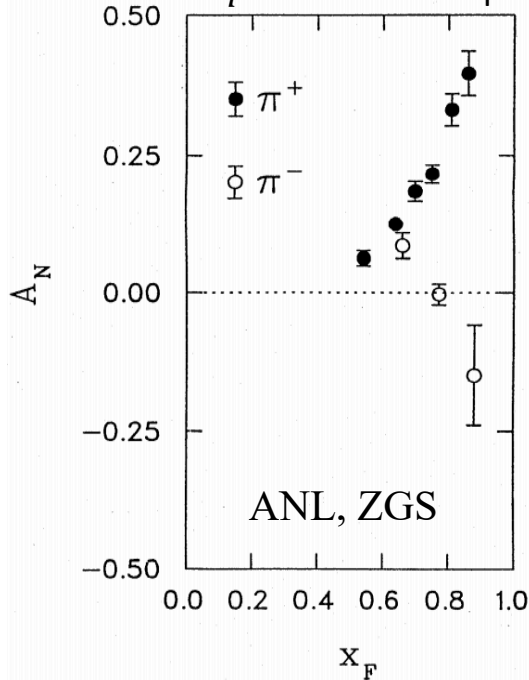
1. Transverse Single-Spin Asymmetry.
2. Sivers Effect in the Nucleon.
3. Sea-quark Sivers Asymmetry from Polarized Drell-Yan.
4. Extracting the Spectrometer-Induced Azimuthal Asymmetry.
5. Summary and Conclusions.

Transverse Single-Spin Asymmetry

How it all started?

W.H. Dragoset et al., PRL36, 929 (1976)

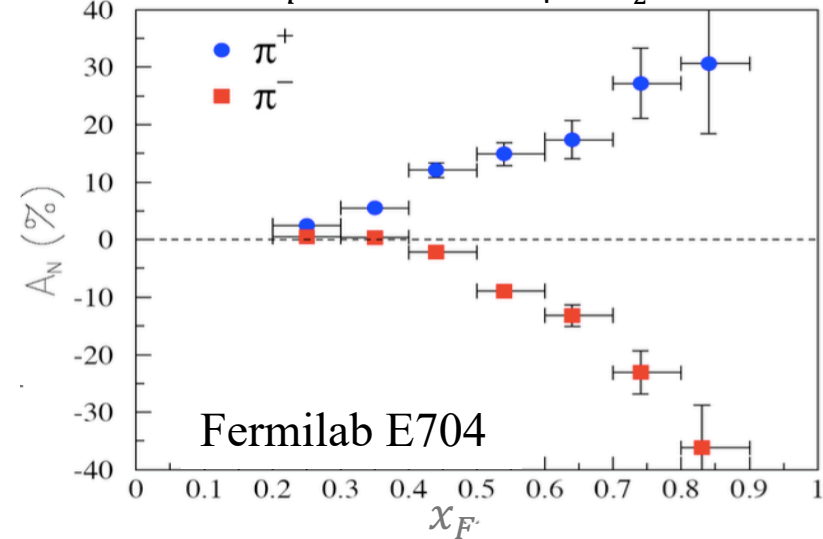
12 GeV p^\uparrow beam with Liquid H_2



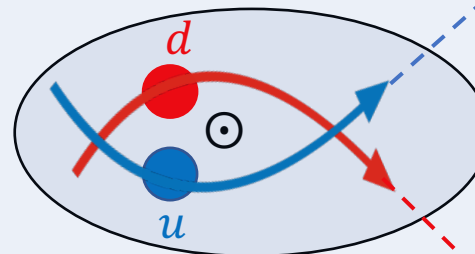
Phys. Lett. B, 268(1991), Pages 462-466

Plot credit: M. Anselmino

200 GeV p^\uparrow beam with Liquid H_2



Dennis Sivers' Idea



⊙ = Transversely Polarized Proton

Plot idea: Caroline Riedl

$\pi^+ (u\bar{d})$

Left-Right asymmetry

$$A_n = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

$\pi^+ (u\bar{d})$ favors left

$\pi^- (d\bar{u})$ favors right

$\pi^- (d\bar{u})$

Sivers Effect in the Nucleon

Reasons for the Asymmetry

The number density of unpolarized quarks in a transversely polarized proton:

$$f_{q/p^\uparrow}(x, \vec{k}_T) = f_1^q(x, k_T^2) - f_{1T}^{\perp q}(x, k_T^2) \frac{(\vec{k}_T \times \vec{S}) \cdot \vec{P}}{m_p}$$

Dennis Sivers, Phys. Rev. D **41**, 83 (1990)

The \vec{k}_T distribution of quarks in a transversely polarized proton can be **asymmetric** and known as **Sivers effect**.

Gives correlation between \vec{k}_T and \vec{S}

f_1^q = Unpolarized quark density.

$f_{1T}^{\perp q}(x, k_T^2)$ = Sivers function.

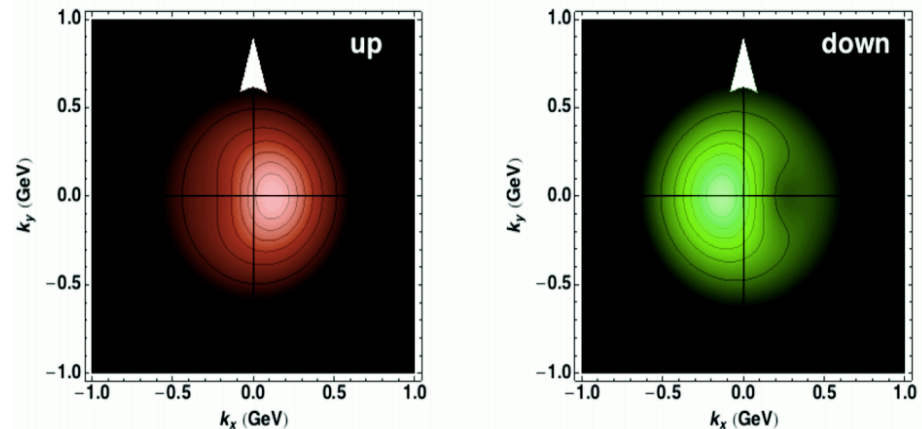
x = Bjorken variable.

\vec{S} = Spin polarization vector.

\vec{P} = Three momentum of the proton.

\vec{k}_T = Intrinsic transverse momentum of unpolarized quarks.

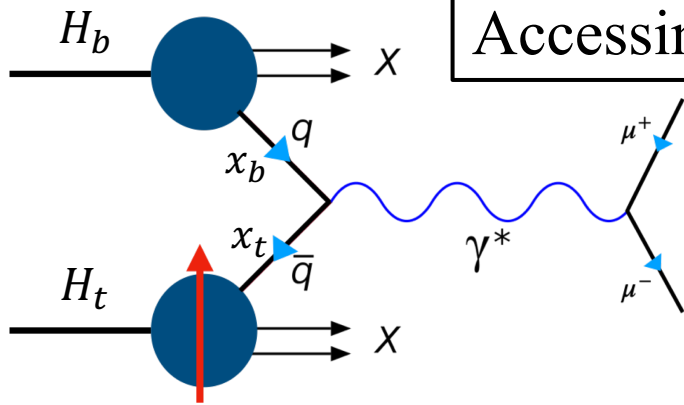
Sivers Effect: Intrinsic k_T imbalance leads to the asymmetry



Bacchetta & Contalbrigo, The proton in 3D

Il Nuovo Saggiatore 28 (12) n.1,2

Sea-quark Sivvers Asymmetry from Polarized Drell-Yan



Accessing Sea-Quarks in SpinQuest

1. Bjorken variable x is the fractional longitudinal momentum carried by the scattered parton.
2. The sea quarks and gluons PDF dominate at low x .
3. Valence quarks dominate at high x .
4. large- x sea quarks and low- x valence quarks are suppressed. Hence most interactions come from high x valence and low x sea quarks.

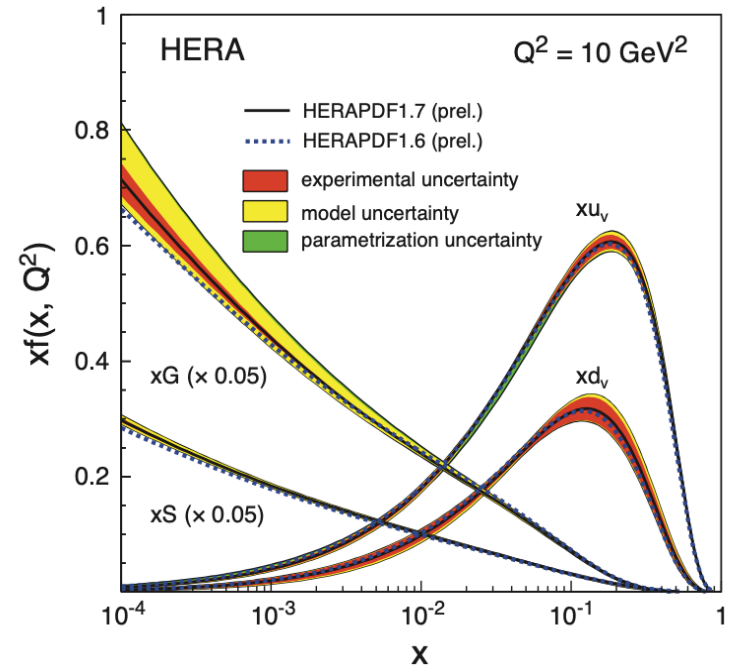


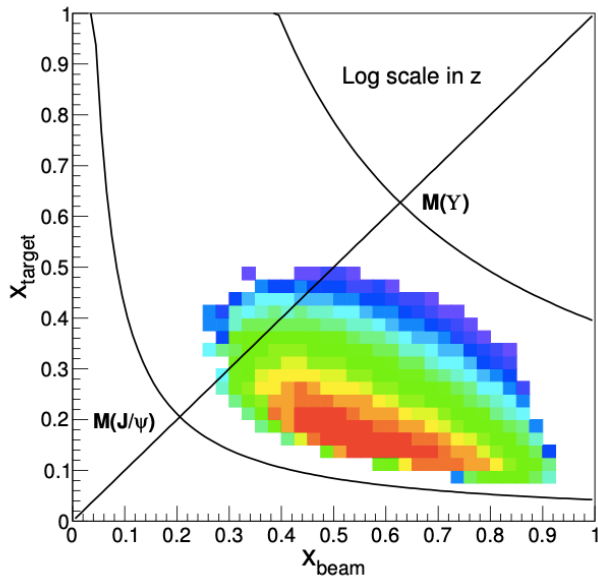
Fig: Proton parton distribution functions plotted as functions of Bjorken x

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t s} \sum_q e_q^2 (q_b(x_b) \bar{q}_t(x_t) + q_t(x_t) \bar{q}_b(x_b))$$

1. For SpinQuest $x_b > x_t$
2. Kinematic acceptance plot in next slide 5

Sea-quark Sivvers Asymmetry from Polarized Drell-Yan

SpinQuest Apparatus



The kinematic acceptance of the SpinQuest experiment. ($x_b > x_t$)

Transversely Polarized NH_3 or ND_3 .

Main Injector Beam
120 GeV Proton

$\gamma^* \rightarrow \mu^+ \mu^-$

300 cm

Upstream Face of FMAG
(x, y, z) = (0, 0, 0)

4.9m

Solid iron focusing magnet, hadron absorber and beam dump (FMAG)

Station 1:
Hodoscope array
MWPC tracking

Momentum measuring magnet (KMag)

Stations 2 and 3:
Hodoscope array
Drift chamber tracking

Station 4:
Hodoscope array
Proportional tube tracking

Hadron absorber (iron wall)

25m

SeaQuest Dimuon Spectrometer

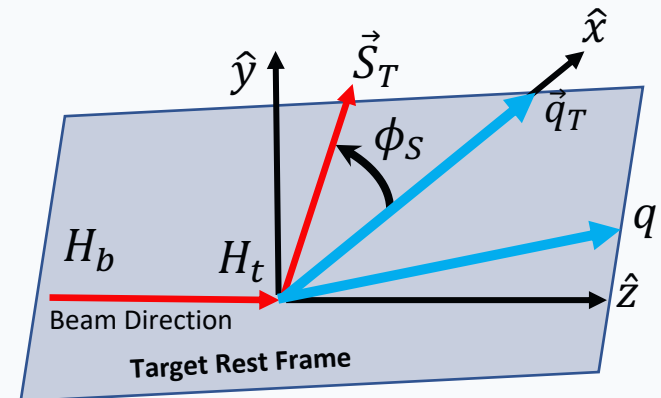
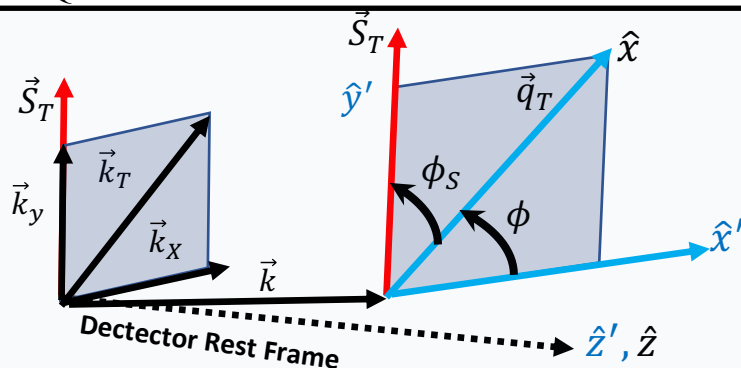
1. Tracking : Abinash Pun
2. FPGA Trigger: MinJung Kim
3. Polarization: Zulkaida Akbar
4. Dilution Factor: Anchit Arora

The Drell-Yan Cross Section in Terms of Sivers Asymmetry:

$$\sigma_{DY}^{\uparrow\downarrow} = \frac{d \sigma^{LO}}{d^4 q \, d\phi_S} \propto 1 \pm |S_T| \sin \phi_S \, A_T^{\sin \phi_S}$$

Phys. Rev. D 79, 034005 (2009),
PRL 119, 112002 (2017)

$$A(\phi_S) = \frac{1}{|S_T|} \frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} = \sin \phi_S A_T^{\sin \phi_S}$$

 $\vec{S}_T =$ Target spin vector
$$\hat{x}, \hat{y}, \hat{z}, \text{ is target rest frame = TF; } \hat{x} = \hat{q}_T, \hat{y} = \hat{z} \times \hat{q}_T$$
 $\hat{x}', \hat{y}', \hat{z}'$ is detector rest frame = DF $\vec{q}_T =$ Dimuon's transverse momentum $\vec{k}_T =$ Quark's transverse momentum

1. $\sigma_{DY}^{\uparrow\downarrow}$ is the Drell-Yan cross section and $A_T^{\sin\phi_S}$ is the Siverson asymmetry.
2. Azimuthal angle ϕ_S in TF and ϕ in DF can be written as $\phi_S^{\uparrow\downarrow} = \left(\pm \frac{\pi}{2} - \phi\right)$.

Extracting the Spectrometer-Induced Azimuthal Asymmetry

Motivation for the Spectrometer-Induced Asymmetry Systematic Check

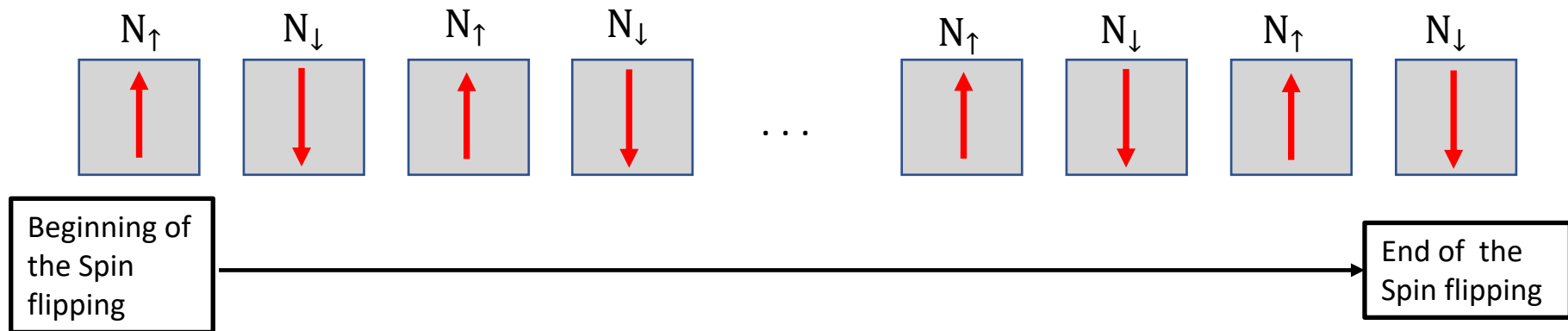
1. The efficiency of the detectors could be changing over time (e.g. the phototubes might suffer a decrease in gain).
 2. The numbers of protons hitting the polarized target will not be the same in each spill, and the detector performance could change due to luminosity fluctuations.
- In either case, it is possible for one target spin state to collect a higher yield than the other, producing a false asymmetry. We will check the size of such effects, by using the SeaQuest experiment dataset.

Extracting the Spectrometer-Induced Azimuthal Asymmetry

Dimuon Yield ($N_{\uparrow\downarrow}$) and Fake Spin Assignment in SeaQuest Data

$$A_n = \frac{\frac{N_{\uparrow}}{L_{\uparrow}^{\text{int}}} - \frac{N_{\downarrow}}{L_{\downarrow}^{\text{int}}}}{\frac{N_{\uparrow}}{L_{\uparrow}^{\text{int}}} + \frac{N_{\downarrow}}{L_{\downarrow}^{\text{int}}}} = S_T A(\phi)$$

$$N_{\uparrow\downarrow}(\phi) = L_{\uparrow\downarrow}^{\text{int}} \Omega \epsilon_T \sigma [1 \pm S_T A(\phi)]$$

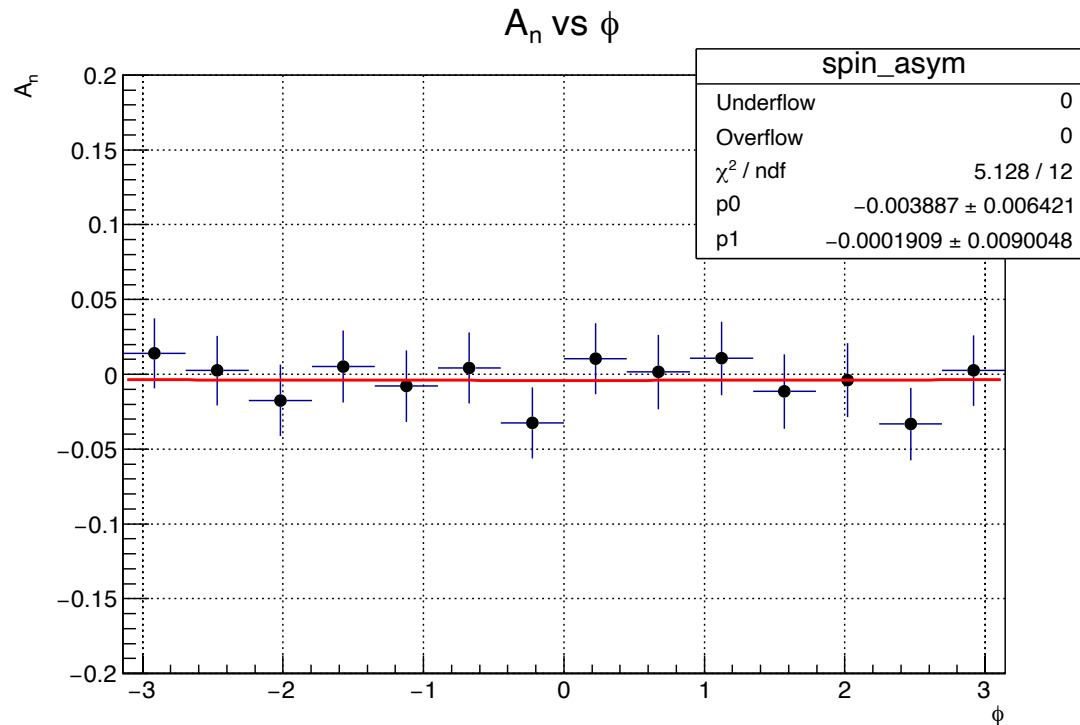


1. σ is the unpolarized interaction cross section.
2. Ω is the overall acceptance of the spectrometer.
3. $L_{\uparrow\downarrow}^{\text{int}}$ is the integrated number of protons hitting the target LH_2 when DAQ is live.
4. S_T is the transverse polarization. We have assumed 1 for the (fake) spin flipping case.
5. ϵ_T overall efficiency of the measurement.
6. $A(\phi)$ can have the form of the detector false asymmetry or physics asymmetry [Sivers](#).

Extracting the Spectrometer-Induced Azimuthal Asymmetry

Flipping Spin Every Hour

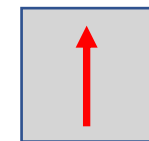
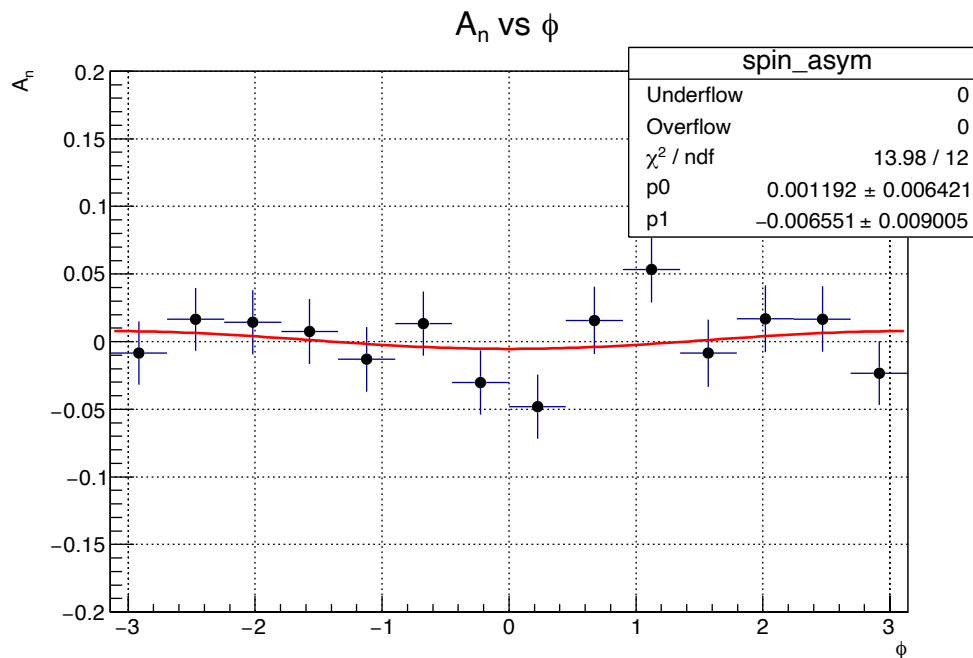
1. Standard SeaQuest selections was used where the dimuon mass was **4.2 GeV** or more.
2. Total protons on LH₂ target is **1.5×10^{17}** and total DAQ runs are analyzed is about **~3000**.
3. Each run is about one hour and only LH₂ target was used from the runs.
4. The fitting function $par[0] + par[1] * \cos \phi$ is used with least-squares method.
5. The asymmetry $Par[1] = -0.0002 \pm 0.0090$
6. From the results we do not see any false spectrometer generated asymmetry produced.



Extracting the Spectrometer-Induced Azimuthal Asymmetry

Flipping Spin Every 12 Hours (Day/Night, a Worst-Case Scenario)

1. Standard SeaQuest selections was used where the dimuon mass was 4.2 GeV or more.
2. Total protons on LH₂ target is 1.5×10^{17} and total DAQ runs are analyzed is about ~3000.
3. Each run is about one hour and only LH₂ target was used from the runs.
4. The fitting function $par[0] + par[1] * \cos \phi$ is used with least-squares method.
5. The asymmetry $Par[1] = -0.007 \pm 0.009$
6. From the results we do not see any false spectrometer generated asymmetry produced.



Day

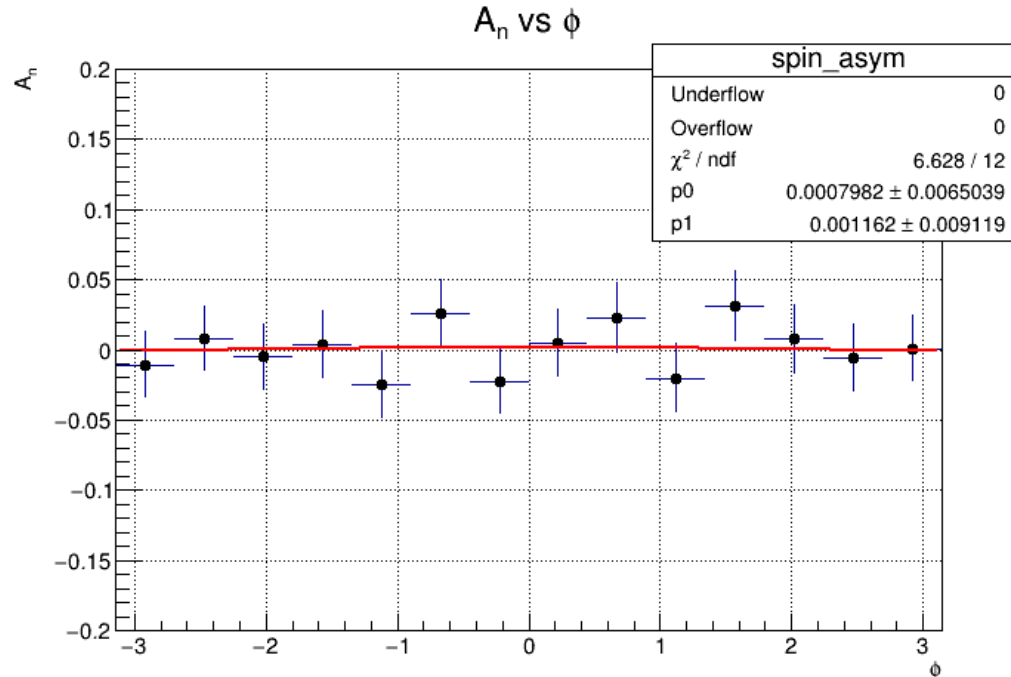


Night

Extracting the Spectrometer-Induced Azimuthal Asymmetry

Flipping Spin Every 50 Hour (a Reasonable Scenario)

1. Standard SeaQuest selections was used where the dimuon mass was 4.2 GeV or more.
2. Total protons on LH₂ target is 1.5×10^{17} and total DAQ runs are analyzed is about ~3000.
3. Each run is about one hour and only LH₂ target was used from the runs.
4. The fitting function $par[0] + par[1] * \cos \phi$ is used with least-squares method.
5. The asymmetry $Par[1] = -0.001 \pm 0.009$
6. From the results we do not see any false spectrometer generated asymmetry produced.



Summary and Conclusions

- We have done a systematic study of measuring the fake azimuthal asymmetries that could be introduced due to the spectrometer.
- We have found that the detector did not generate a false azimuthal asymmetry that could imitate the physics Sivers asymmetry.

Thanks to all SeaQuest collaborators, especially Kenichi Nakano and Andrew Chen for all the suggestions and comments in the study.

Thanks For Listening & Welcome to Join the SpinQuest Collaborations

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Back Up Slides

Sivers Effect in the Nucleon

Quarks Distributions in Impact Parameter Space

A transversely polarized proton deformation is described by the gradient of the Fourier transform of $E_q(x, \xi = 0, -\Delta_\perp^2)$.

M. Burkardt, *Few-Body Syst* **52**, 265–270 (2012)

$$q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} H^q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp} - \frac{1}{2M} \frac{\partial}{\partial b_y} \int \frac{d^2 \Delta_\perp}{(2\pi)^2} E^q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp}$$

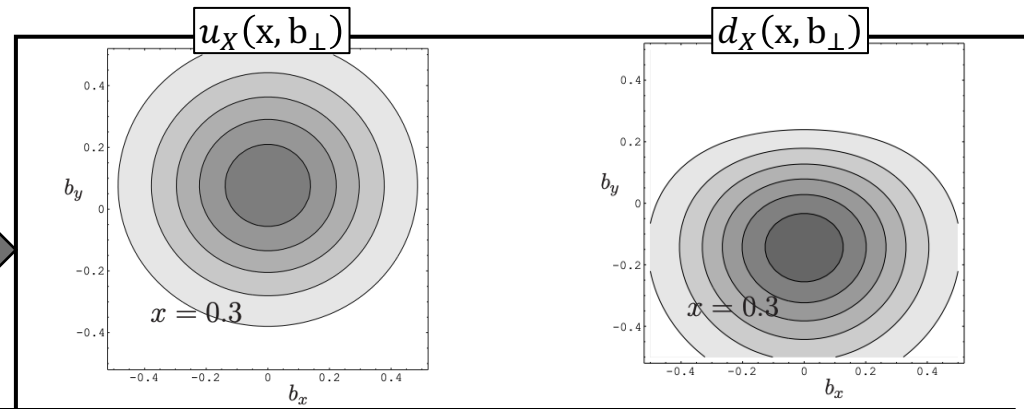
$$d_y^q \equiv \int d^2 b_\perp q(x, b_\perp) b_y = \frac{k_q}{2M} \quad ; \text{ Positive (negative) drift for the up (down) quark}$$

M. Burkardt, *Int.J.Mod.Phys.A* **18** (2003) 173-208

Anomalous magnetic moments of the quarks
[considering the u and d quarks only]

- $\kappa_p = \frac{2}{3}\kappa_u - \frac{1}{3}\kappa_d = 1.79$
- $\kappa_n = \frac{2}{3}\kappa_d - \frac{1}{3}\kappa_u = -1.91$
- $\kappa_u = 1.673; \quad \kappa_d = -2.033$

IMF Frame

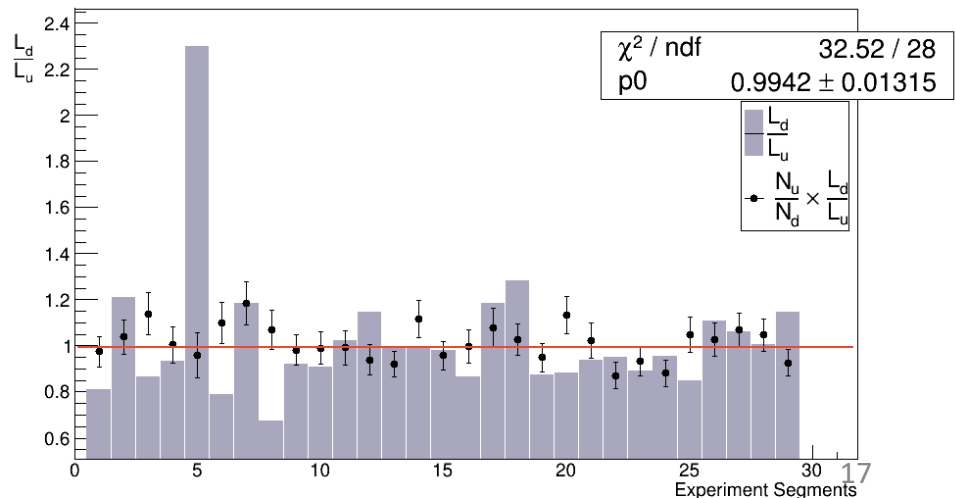
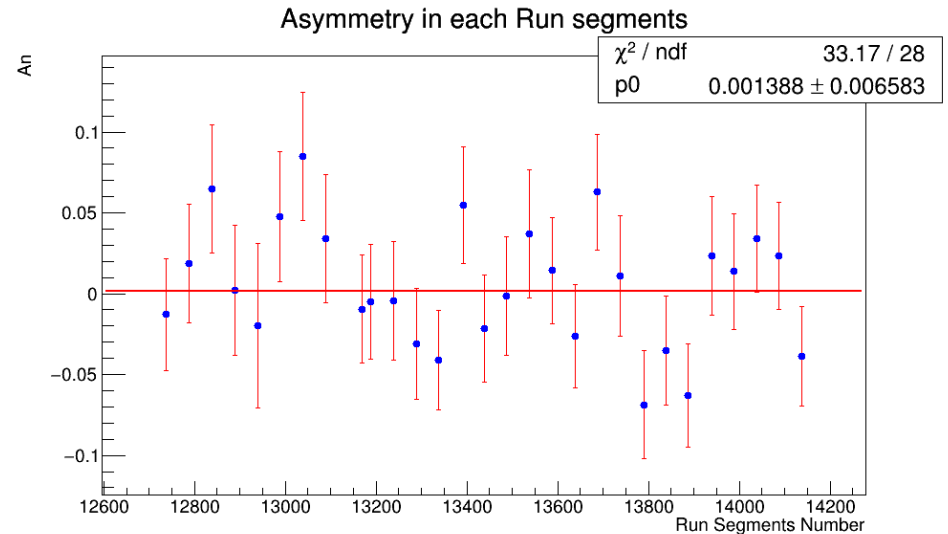


Quarks distributions in **impact parameter space**, where the proton is transversely polarized in x direction.

The reason u and d quarks are drifting in opposite directions is due to the anomalous magnetic moment of the quarks to the proton.

Time Dependent Spectrometer-Induced Asymmetry

1. Each segment consists of range of **100 DAQ runs**. If any runs are missing in any segment, we will have less than 100 runs in that case.
2. Polynomial fit pol0 to the $F = \frac{N_{\uparrow}}{N_{\downarrow}} \times \frac{L_{\downarrow}}{L_{\uparrow}}$ is consistent with 1, and we also have 0 asymmetry with time.

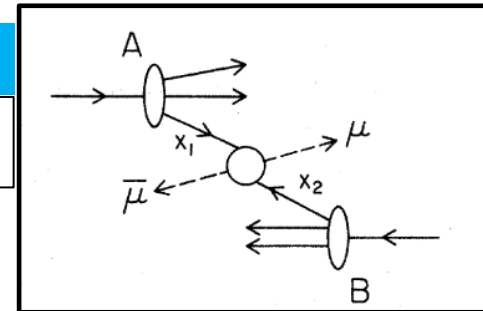


Sea-quark Sivvers asymmetry from polarized Drell-Yan

What is the Drell-Yan Process?

First Explained

Sidney D. Drell and Tung-Mow Yan
Phys. Rev. Lett. 25, 902 (1970)



VOLUME 25, NUMBER 21

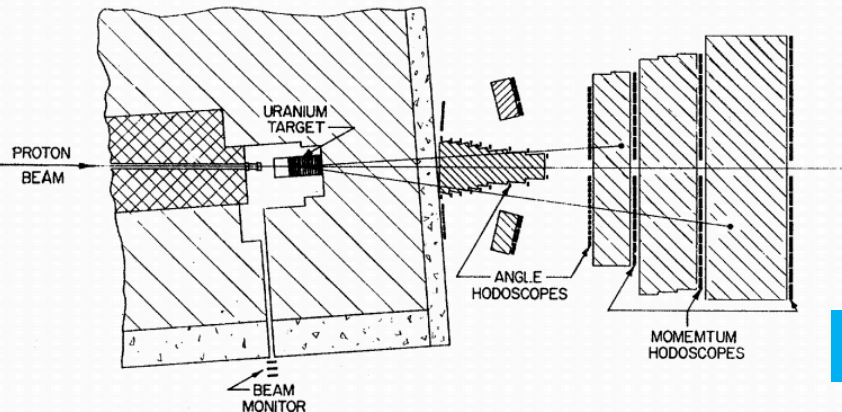
PHYSICAL REVIEW LETTERS

23 NOVEMBER 1970

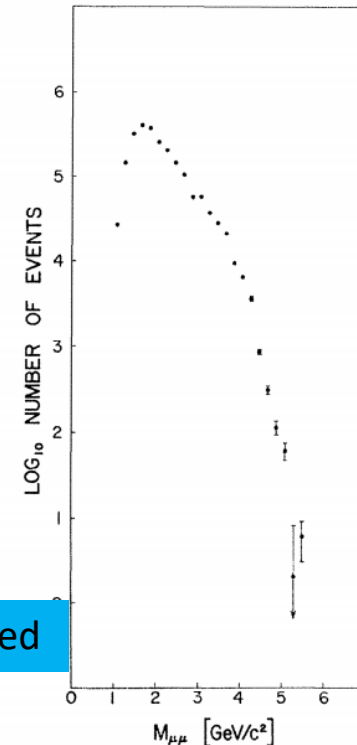
Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)



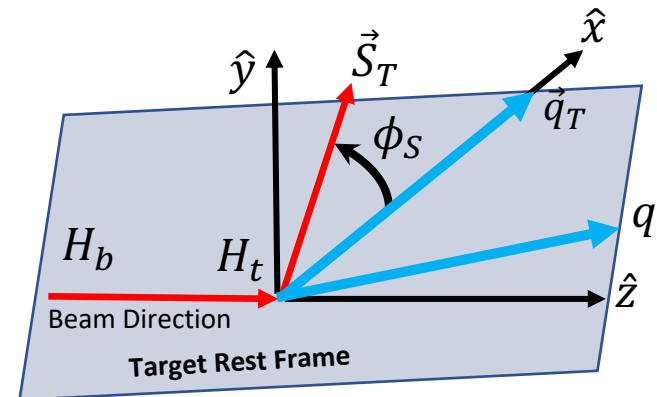
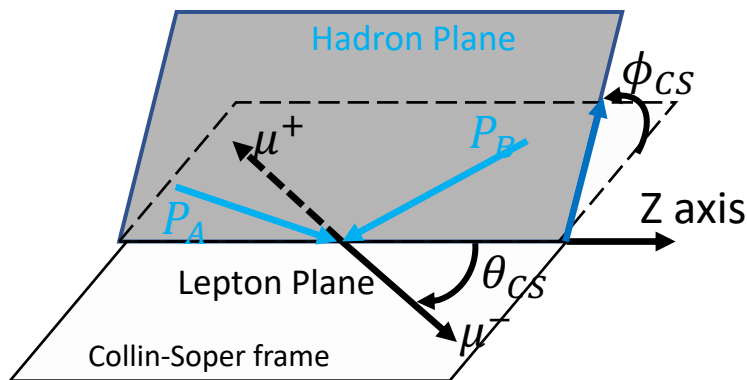
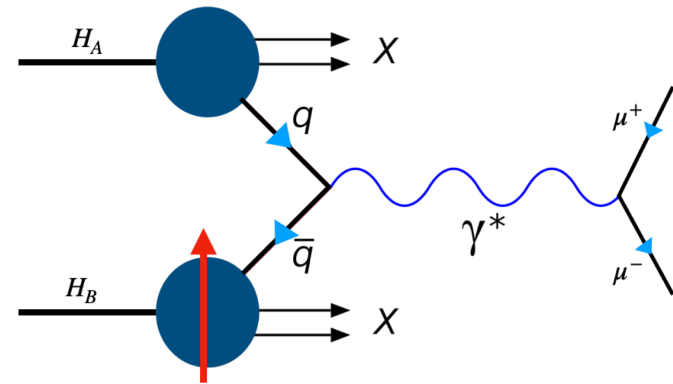
First Observed



Drell Yan Cross Section Formula & Azimuthal Asymmetry

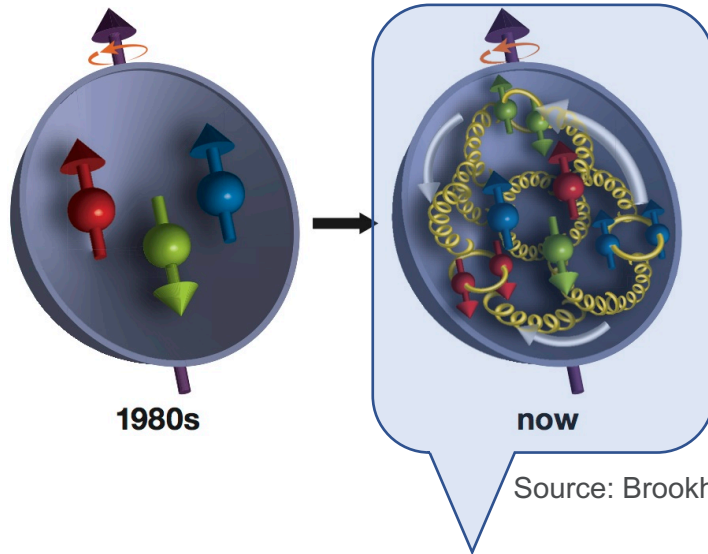
The leading order transversely single Drell-Yan cross section in QCD parton model:

$$\frac{d\sigma^{LO}}{d^4q d\Omega} \propto \hat{\sigma} \left\{ 1 + D_{\sin^2\theta} \cos(2\phi_{CS}) A_U^{2\phi_{CS}} \right. \\ \left. + S_T \left\{ \begin{array}{l} \sin\phi_S A_T^{\sin\phi_S} \\ + \sin(2\phi_{CS} + \phi_S) A_T^{\sin(2\phi_{CS} + \phi_S)} \\ + \sin(2\phi_{CS} + \phi_S) A_T^{\sin(2\phi_{CS} + \phi_S)} \end{array} \right\} \right\}$$



Sea-quark Sivvers Asymmetry from Polarized Drell-Yan

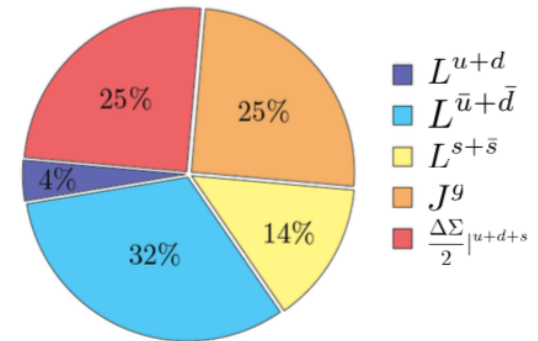
How all the particles inside the proton give it a 1/2 spin?



$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

Predictions from Lattice QCD

Lattice QCD: K.-F. Liu *et al* arXiv:1203.6388



1. Quarks spin accounts for about 25% of the proton's spin.
2. From recent study of **RHIC**, it is still disputed that the sum of both quark and gluon spin contributions make up the total proton spin.
3. **Lattice QCD** indicates that ~**50%** comes from the quark's orbital angular momentum.
4. Hence, *orbital angular momentum of sea quarks could play major role in proton Spin.*
Hints of sea quark O.A.M.

Sea-quark Sivers Asymmetry from Polarized Drell-Yan

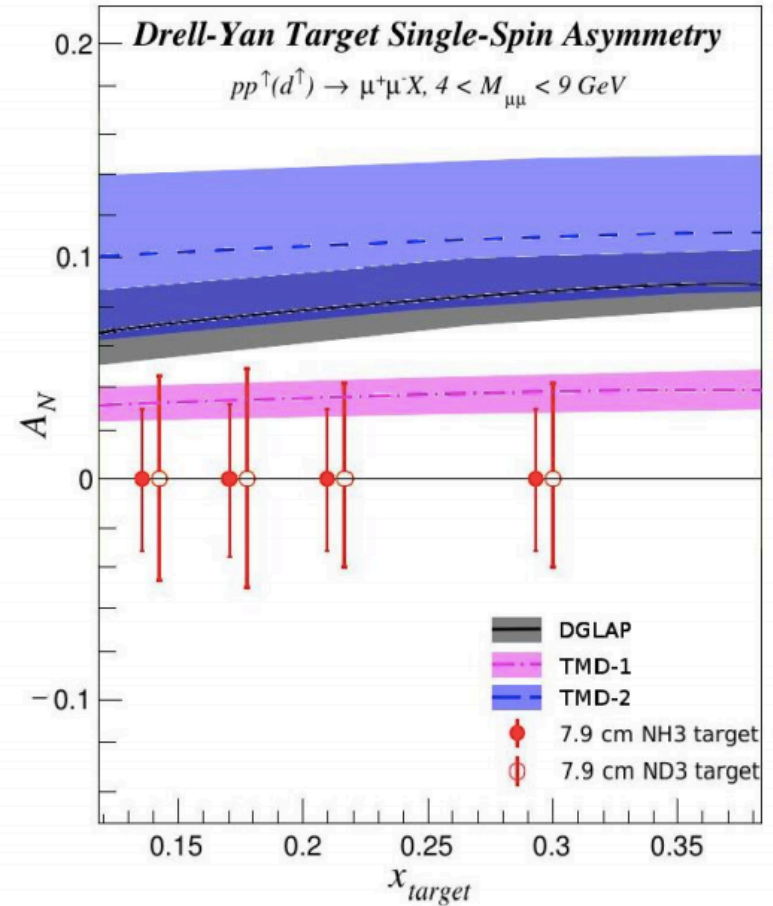
Anticipated Results from SpinQuest

If $A_{Siv} \neq 0$

1. If the Sivers asymmetry $A_{Siv} \neq 0$, we will find a strong evidence that orbital momentum of sea quarks are not zero.
2. We will determine the Sivers function as well.

If $A_{Siv} = 0$

Flavor asymmetry of sea quarks would be more difficult to understand.



DGLAP: M. Anselmino et al arXiv:1612.06413
 TMD-1: M. G. Echevarria et al arXiv:1401.5078
 TMD-2: P. Sun and F. Yuan arXiv:1308.5003

The anticipated uncertainties in the SpinQuest experiment are based on combined running on NH_3 and ND_3 targets.